Development of a chirped pulse laser for cooling positronium

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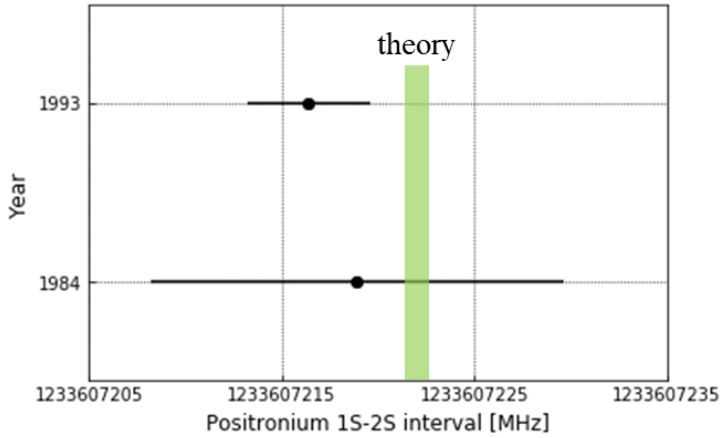
7 KOREA UNIVERSITY College of Science

12.5th International Workshop on Positron and Positronium Chemistry (PPC 12.5)
31 August 2021

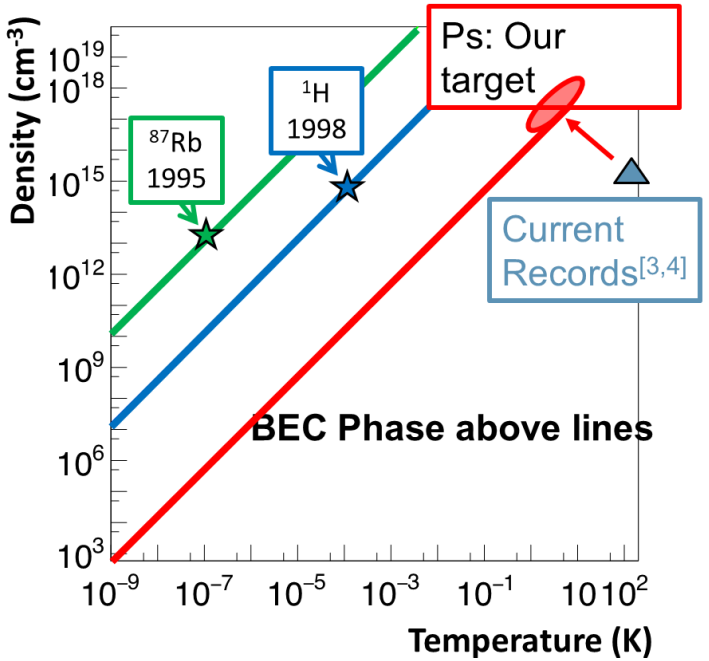
The benefits from a cooled gas of Ps below 10 K

Precision spectroscopy of Ps
(Measurement of 1S-2S transition frequency)



[1] S. Chu *et al.*, P*hysics Review Letters*, 52, 1689 (1984)
[2] M. S. Fee *et al.*, P*hysics Review Letters*, 70, 1397 (1993)

Realization of the first BEC of antimatter



[3] S. Mariazzi *et al.* P*hysics Review Letters,* 104, 243401 (2010)
[4] D. Cassidy *et al. physica status solidi,* 4, 3419 (2007)

<Our Goal>

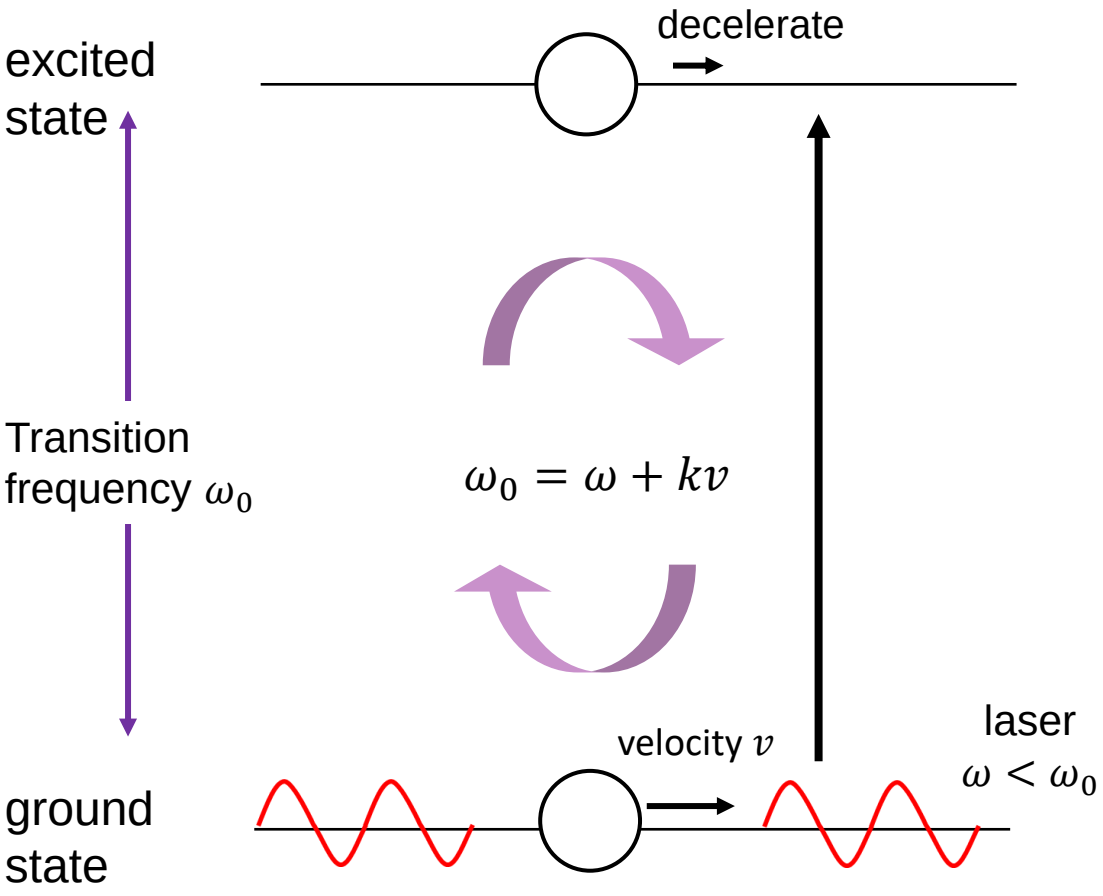
Realization of
the first Bose-Einstein Condensation of antimatter using positronium(Ps)

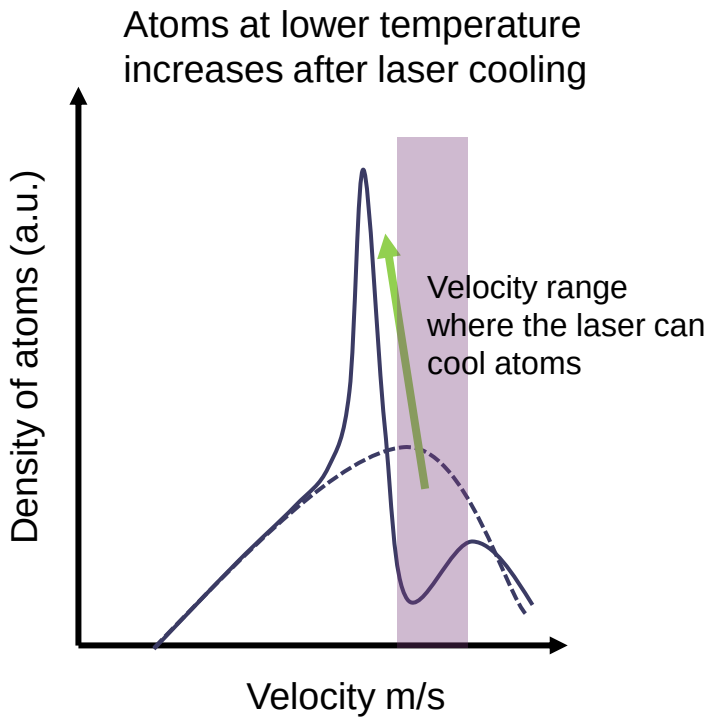
<Main Challenges>

1. Instant production of dense Ps
2. Rapid cooling of Ps
   Cooling Ps atoms to around 10 K
   in a few hundred nano-seconds
   (Critical temperature is 14 K at 10^{18} /cm^3)

Challenges of laser cooling
for rapid cooling of Ps below 100 K

Principle of laser cooling

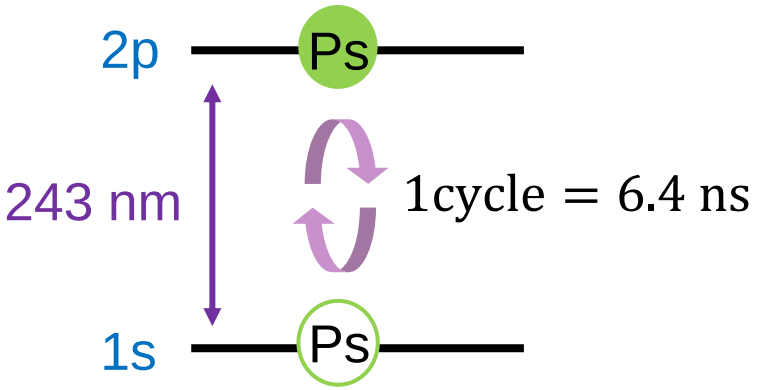




Recoil velocity : $\frac{\hbar\omega}{mc}$ (ex. Rb : 5.9×10^{-3} m/s, Ps : 1.5×10^{3} m/s)

The requirements for laser cooling of Ps

Finish cooling before annihilation

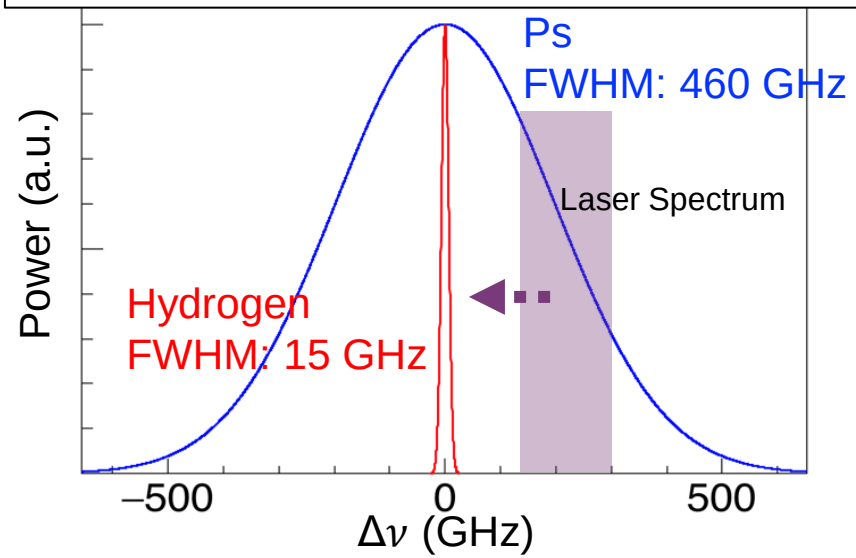


Cooling Ps from 300 K to 10 K requires about 50 excitation cycles.

➡ Long pulse duration about 300 ns (at 243 nm)

Large Doppler broadening

Doppler profile for Hydrogen and Ps at 300 K

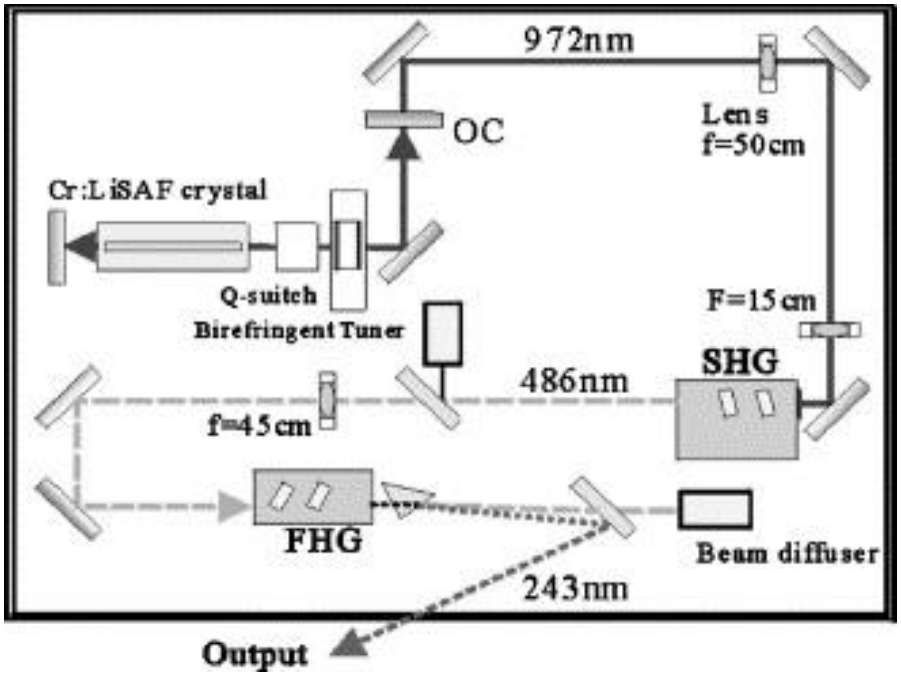


The Doppler broadening of Ps is large because of its small mass

➡
- Broadband laser (FWHM: 150 GHz)
- Frequency-chirped laser (200 GHz/μs)

Previous research on cooling laser of Ps

Cooling laser proposed in the previous research[3]



[3] T. Kumita, *et al. Nuclear Instruments and Methods in Physics Research Section B*, **192**, 171 (2002).

Requirements for laser cooling of Ps

- The wavelength of the cooling laser is adjustable for exciting 1S-2P transition
- Bandwidth is about 150 GHz
- Frequency chirp is necessary for effective cooling
- Pulse duration is about 300 ns

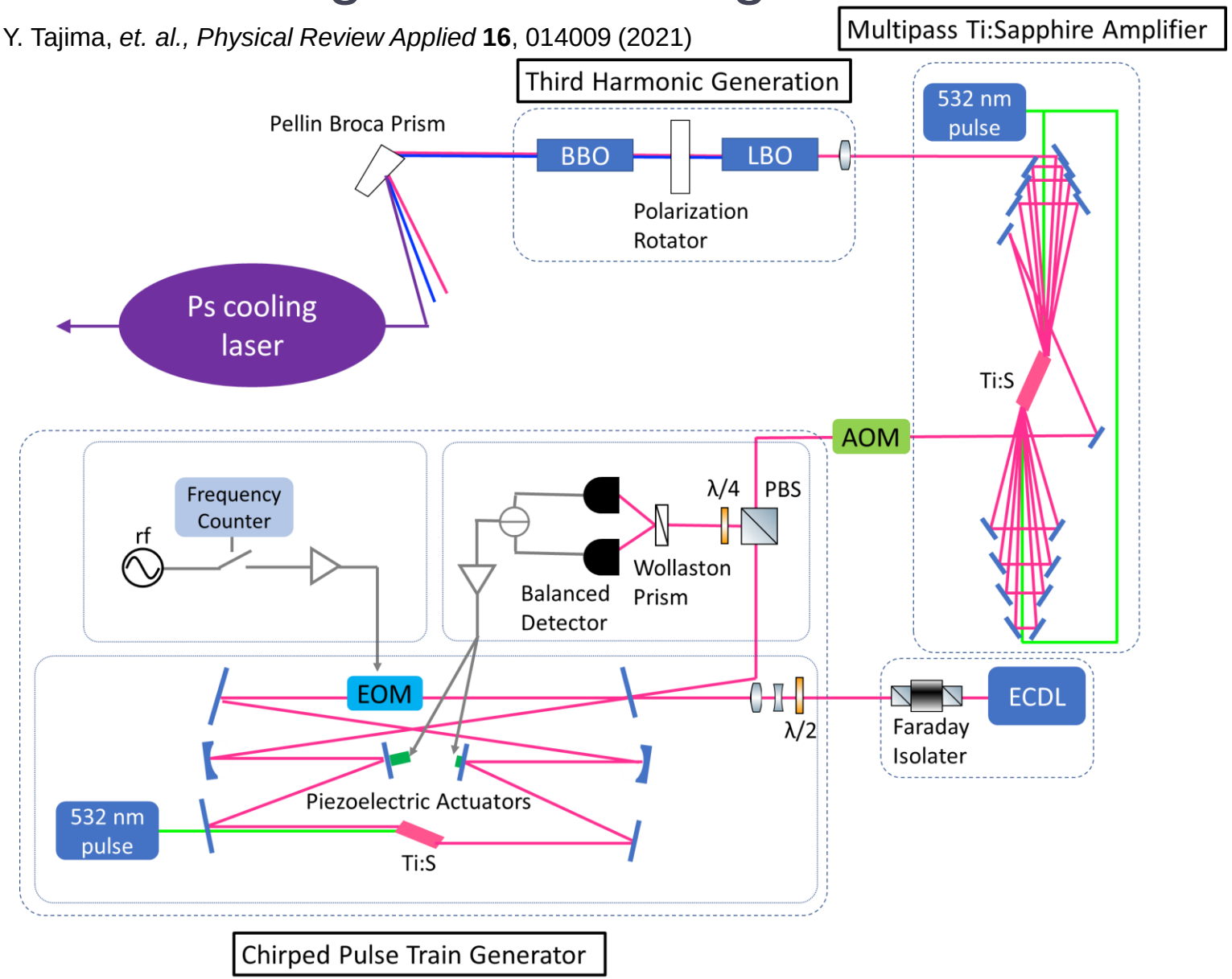
⟺

The characteristics of the laser system

- The wavelength of the output laser pulse is around 243 nm but not sufficiently reproducible
- The bandwidth of this laser is about 86 GHz
- Frequency chirp is not achieved
- Pulse duration is 280 ns

Schematic diagram of cooling laser

K. Yamada, Y. Tajima, *et. al., Physical Review Applied* **16**, 014009 (2021)



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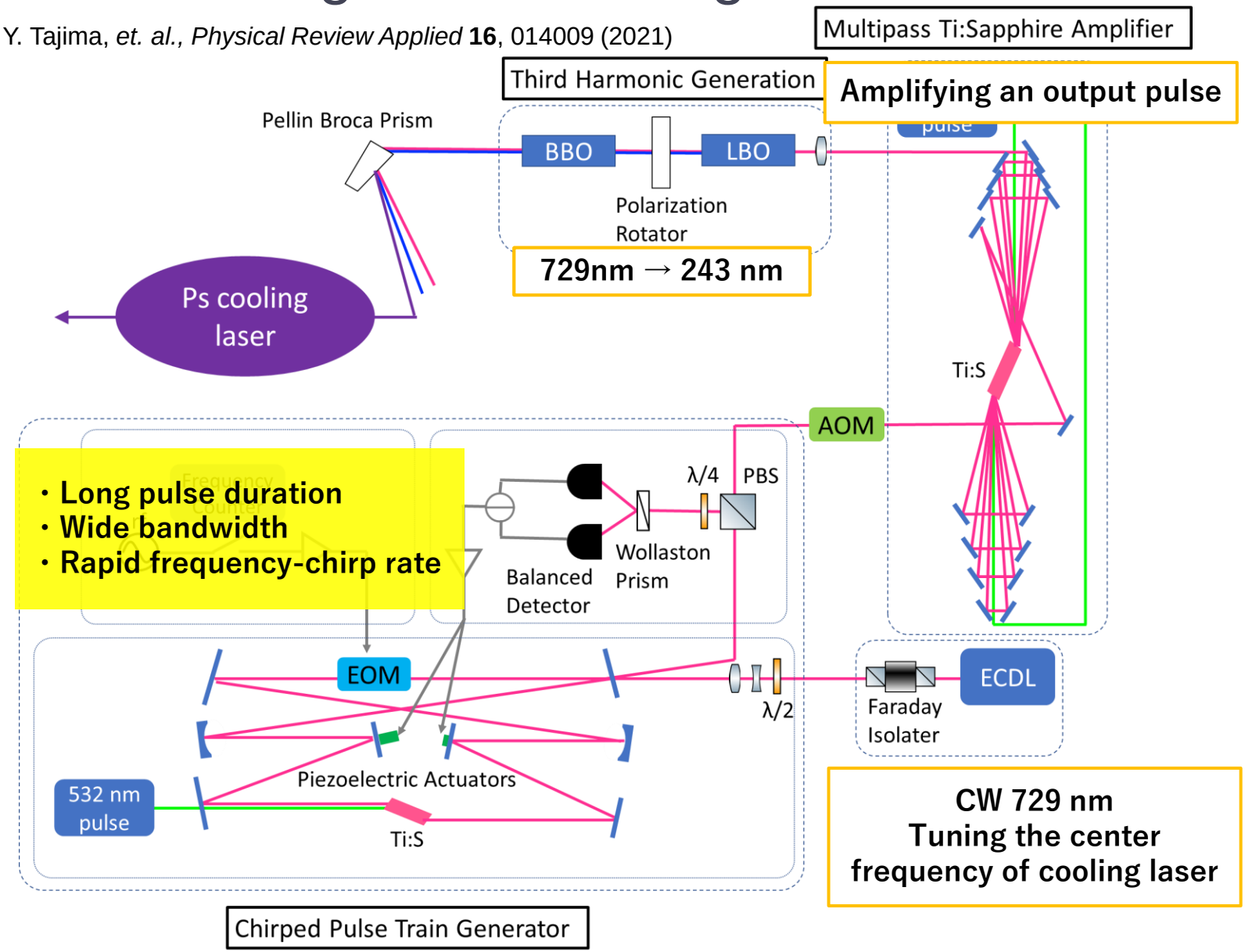

Schematic diagram of cooling laser

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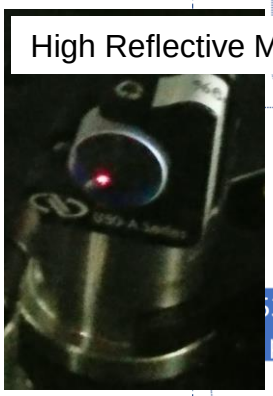
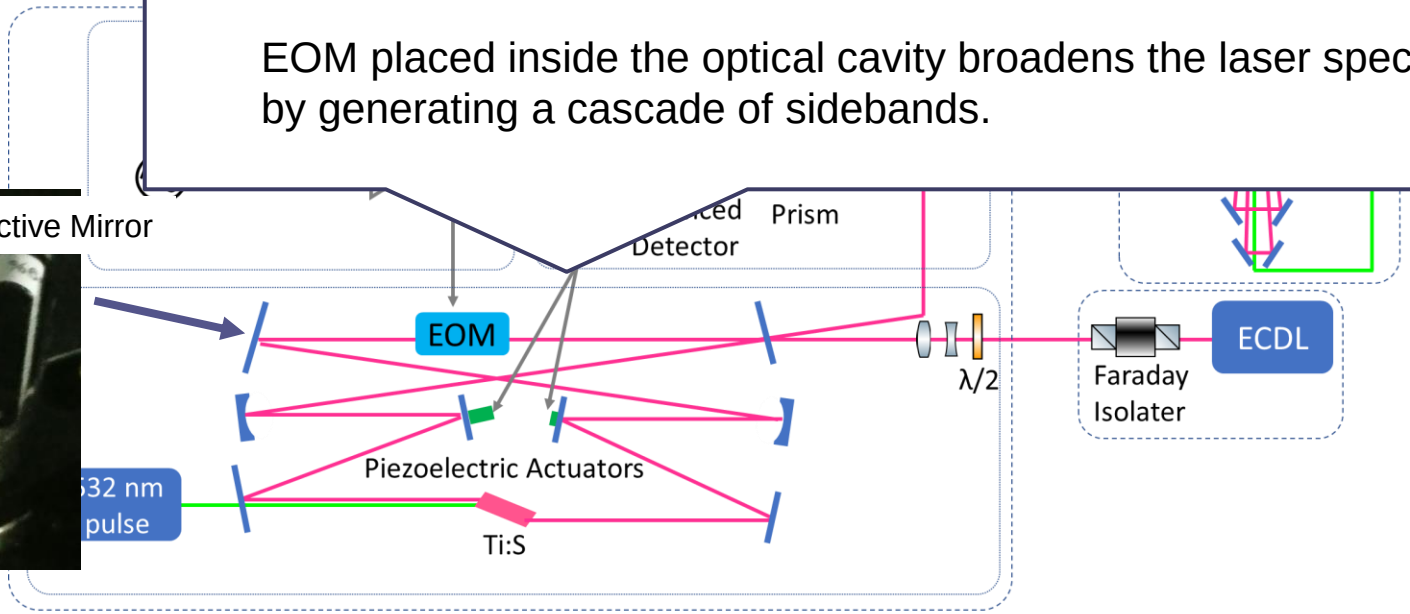
Multipass Ti:Sapphire Amplifier

Spectral broadening by EOM

Single mode → EOM → Electro-optics modulator (EOM) creates sidebands in frequency domain

EOM placed inside the optical cavity broadens the laser spectrum by generating a cascade of sidebands.



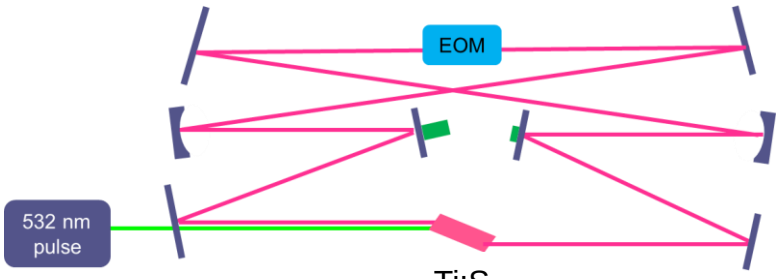


Chirped Pulse Train Generator

Schematic diagram of cooling laser

K. Yamada, Y. Tajir

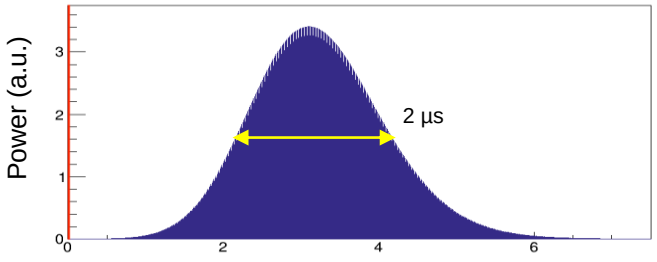
Chirped Pulse Train Generator



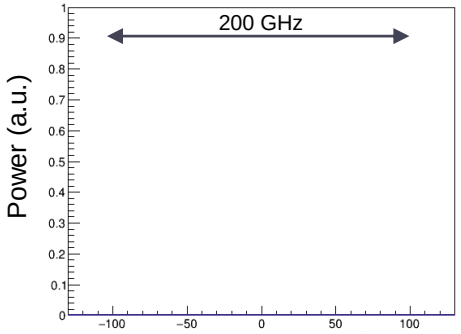
Appling a pulse gain while driving EOM realizes

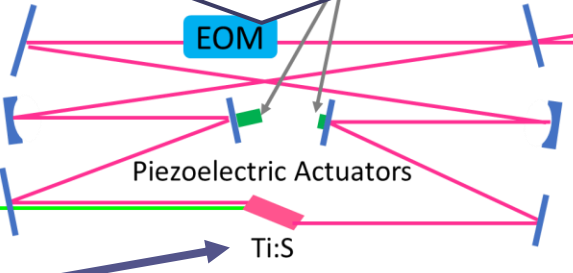
- Long pulse duration
- Broadband laser
- frequency-chirped laser

Power waveform

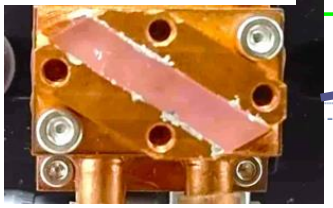


Spectrum at different timings

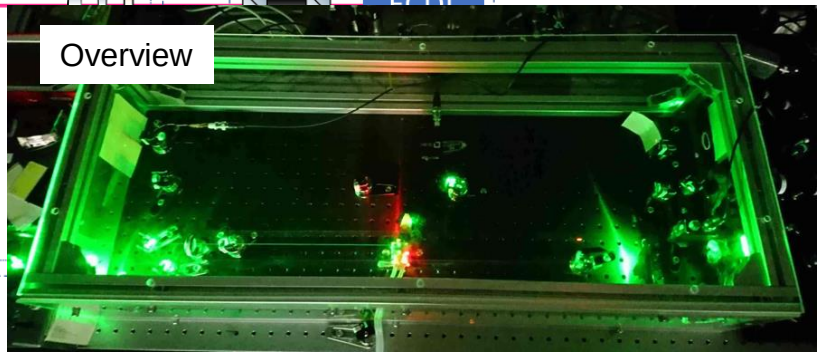




Ti:Sapphire Crystal



Chirped Pulse Train Generator



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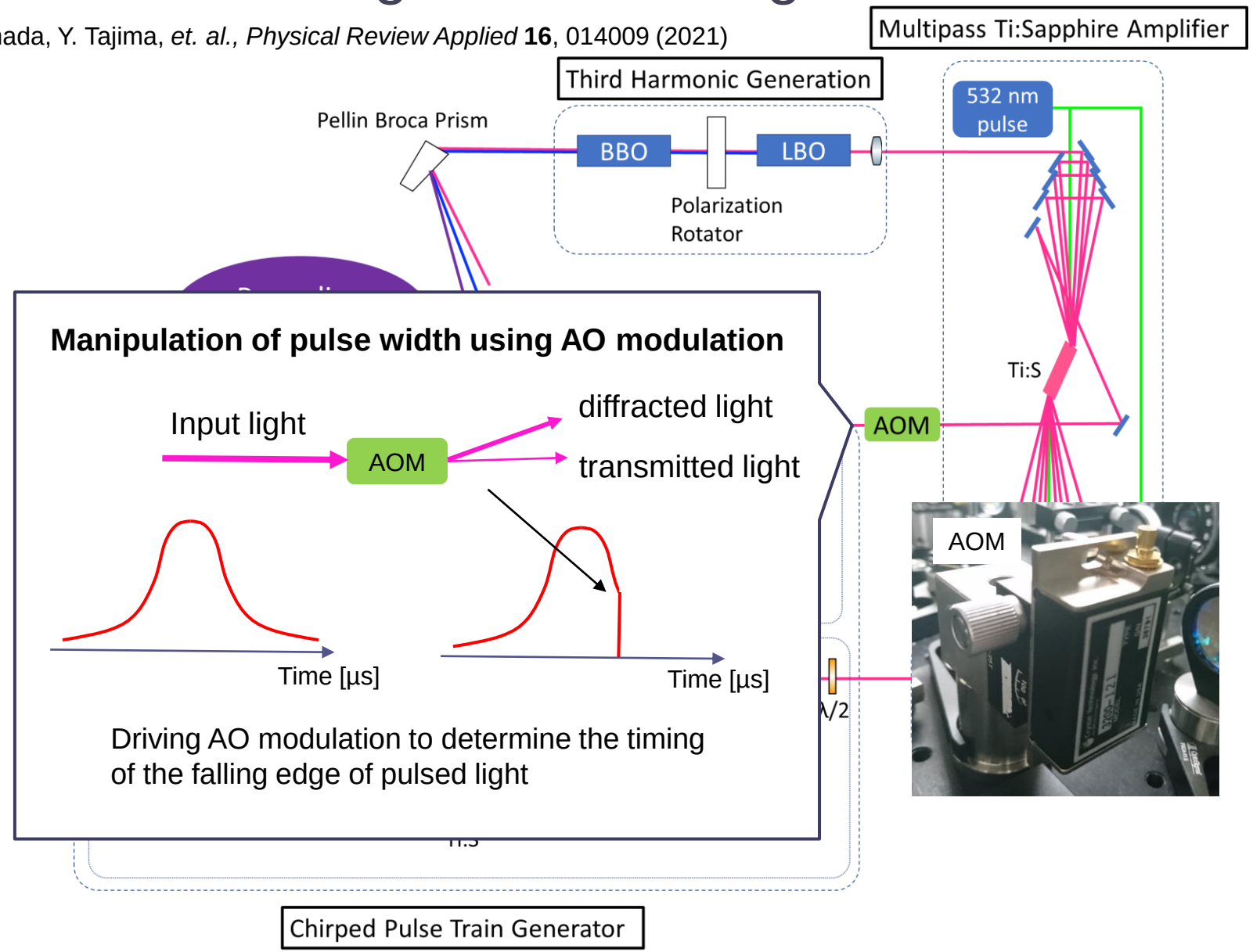

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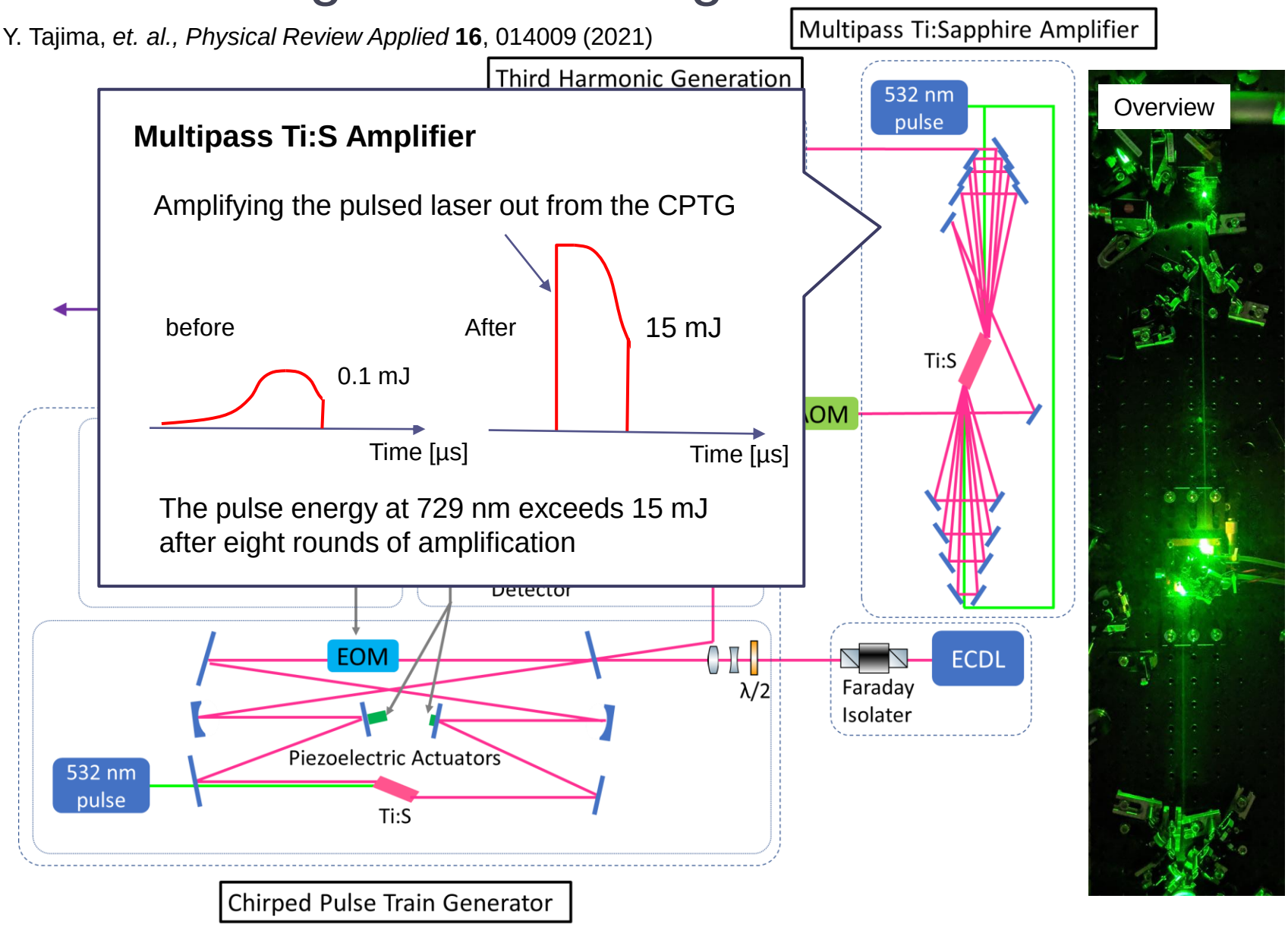

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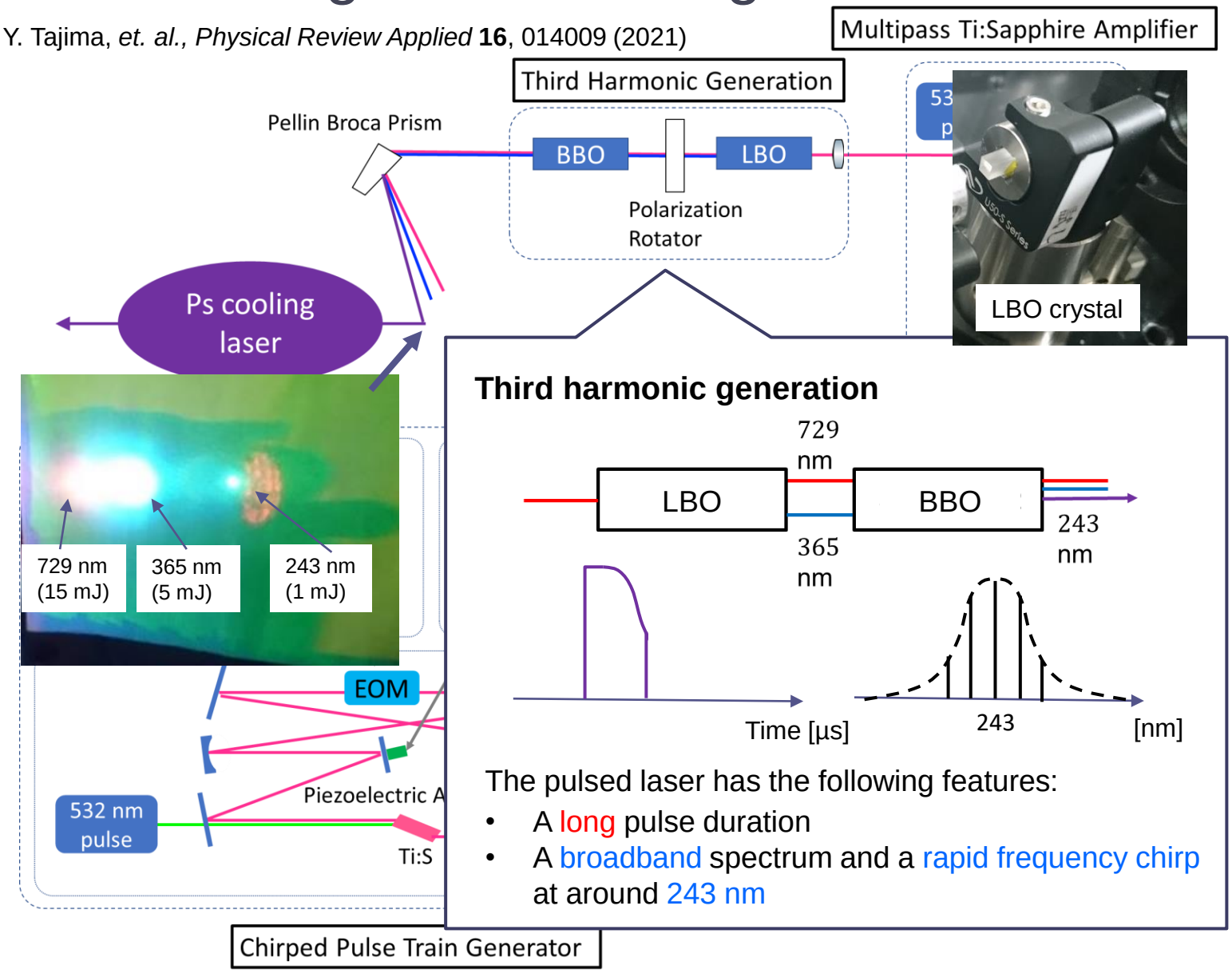
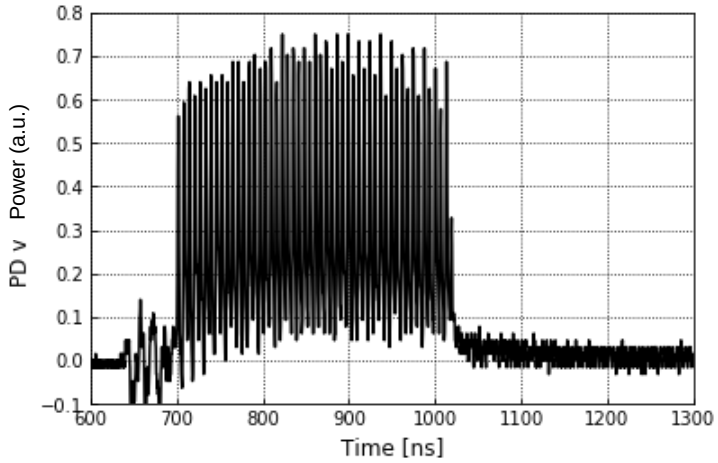


The pulsed laser has the following features:

- A long pulse duration
- A broadband spectrum and a rapid frequency chirp at around 243 nm

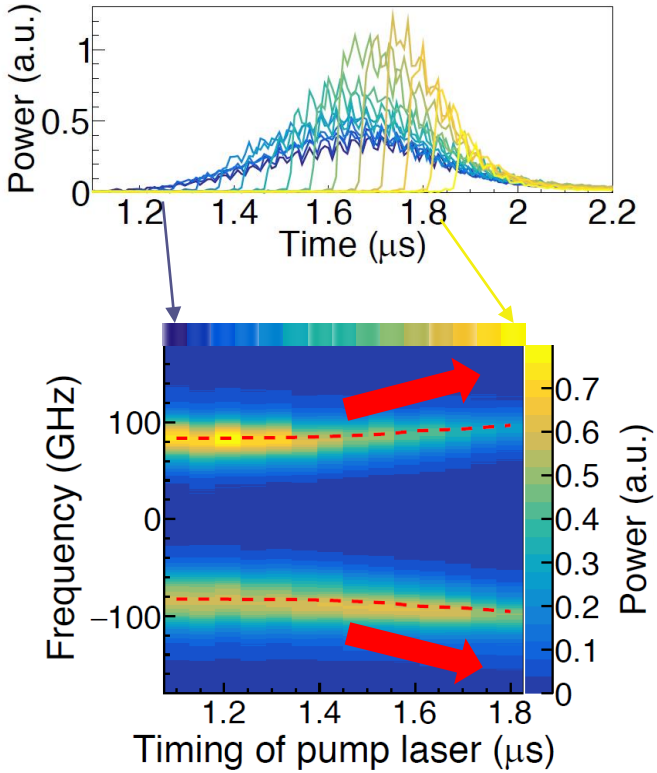
Demonstration of properties of cooling laser

Power waveform at 243 nm

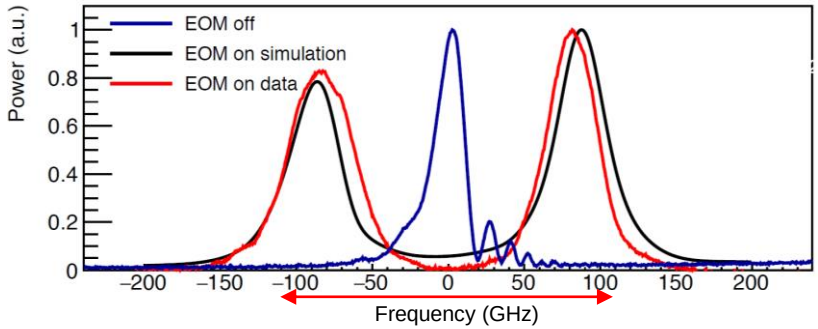


Observing frequency chirp

Changing the timing of the pump laser for the multipass amplifier

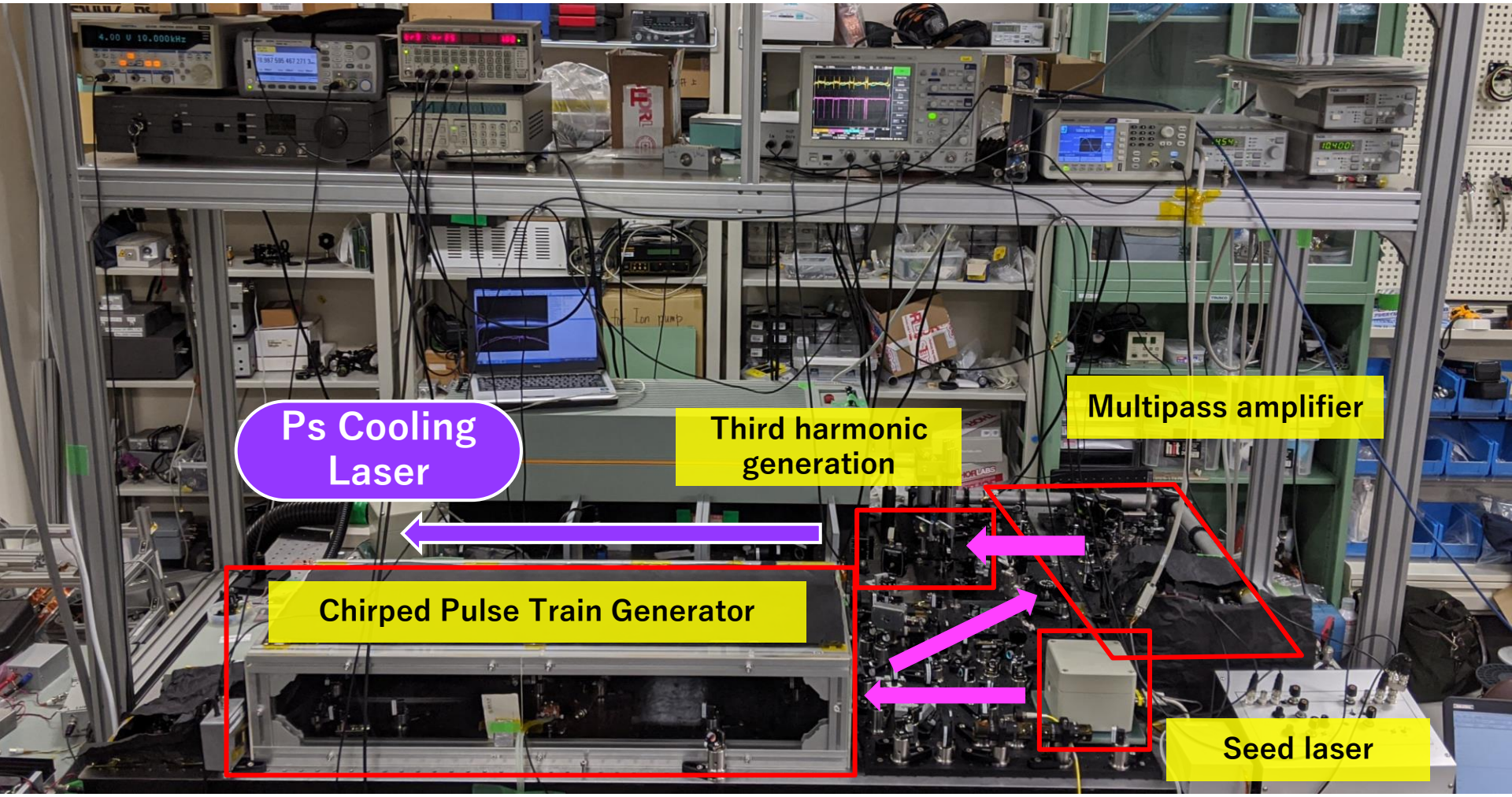


Time-integrated spectrum

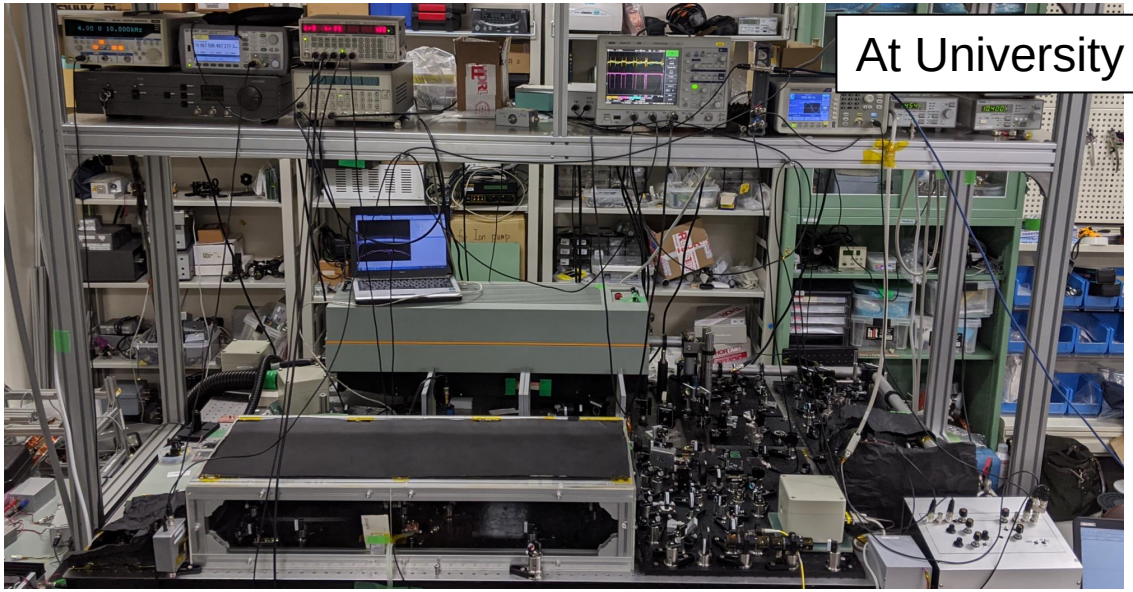


- **Center frequency : 1S-2P transition frequency – 120 GHz**
- **Pulse width : > 300 ns**
- **Pulse energy : 1 mJ**
- **Bandwidth : 200 GHz**
- **Chirp rate : ± 42 GHz/μs**

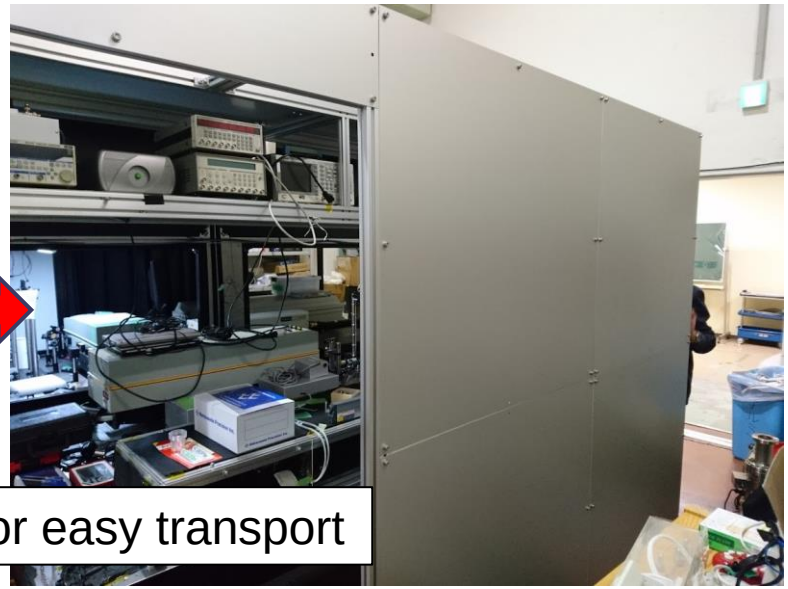
Overview of the cooling laser (2.0 m × 1.1 m)



Laser transport

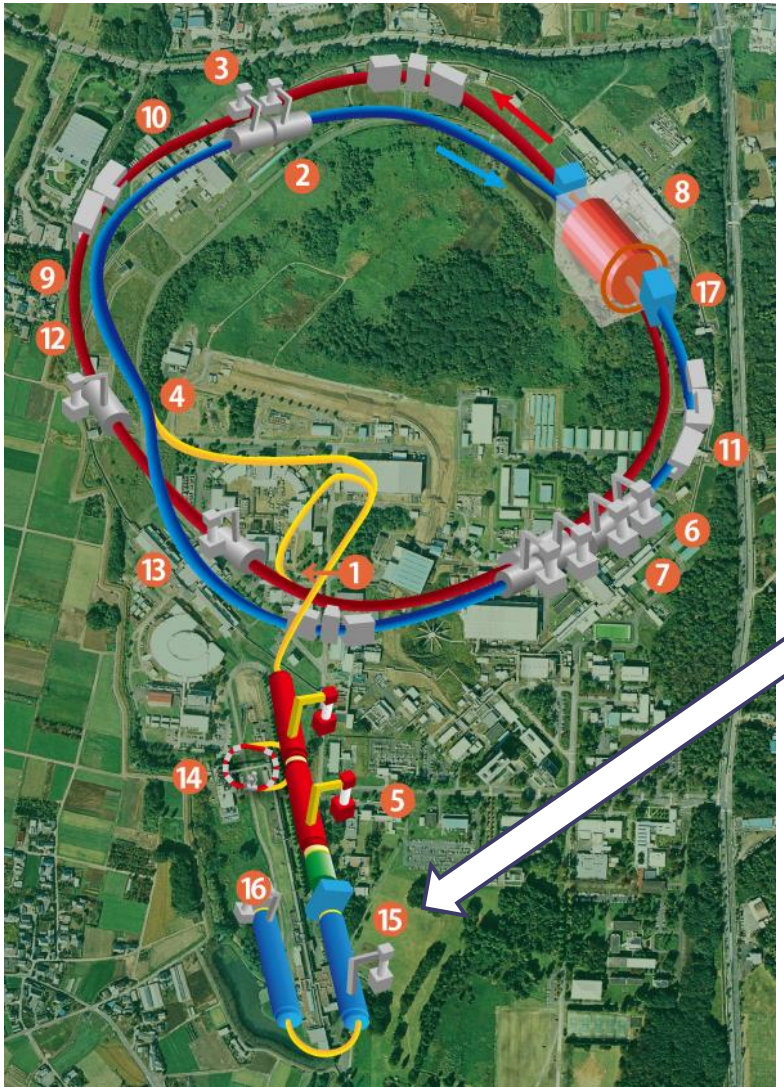


At University of Tokyo

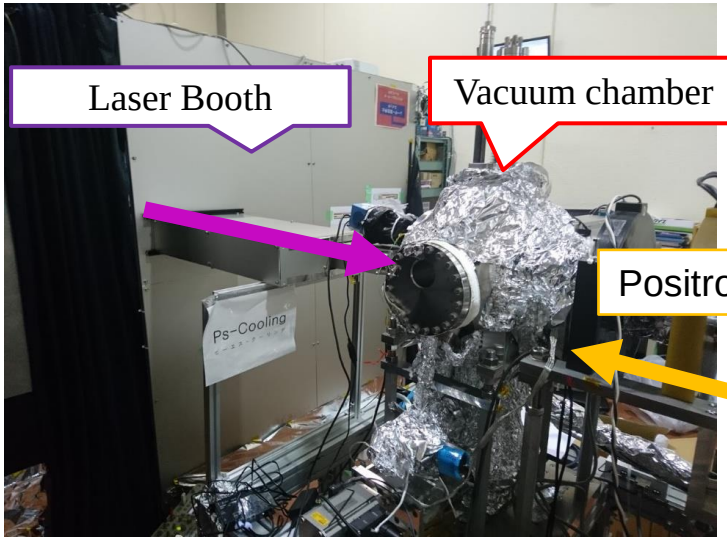


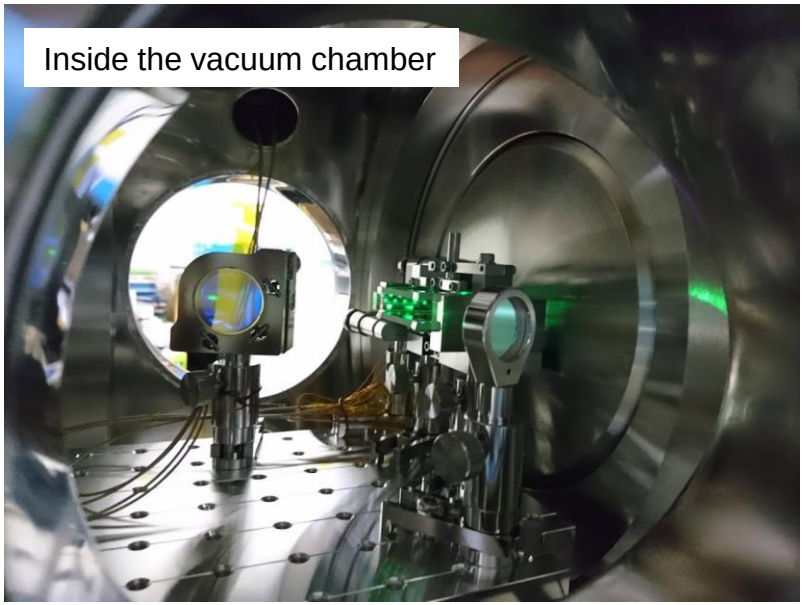
The compact laser for easy transport

Laser cooling experiment at KEK

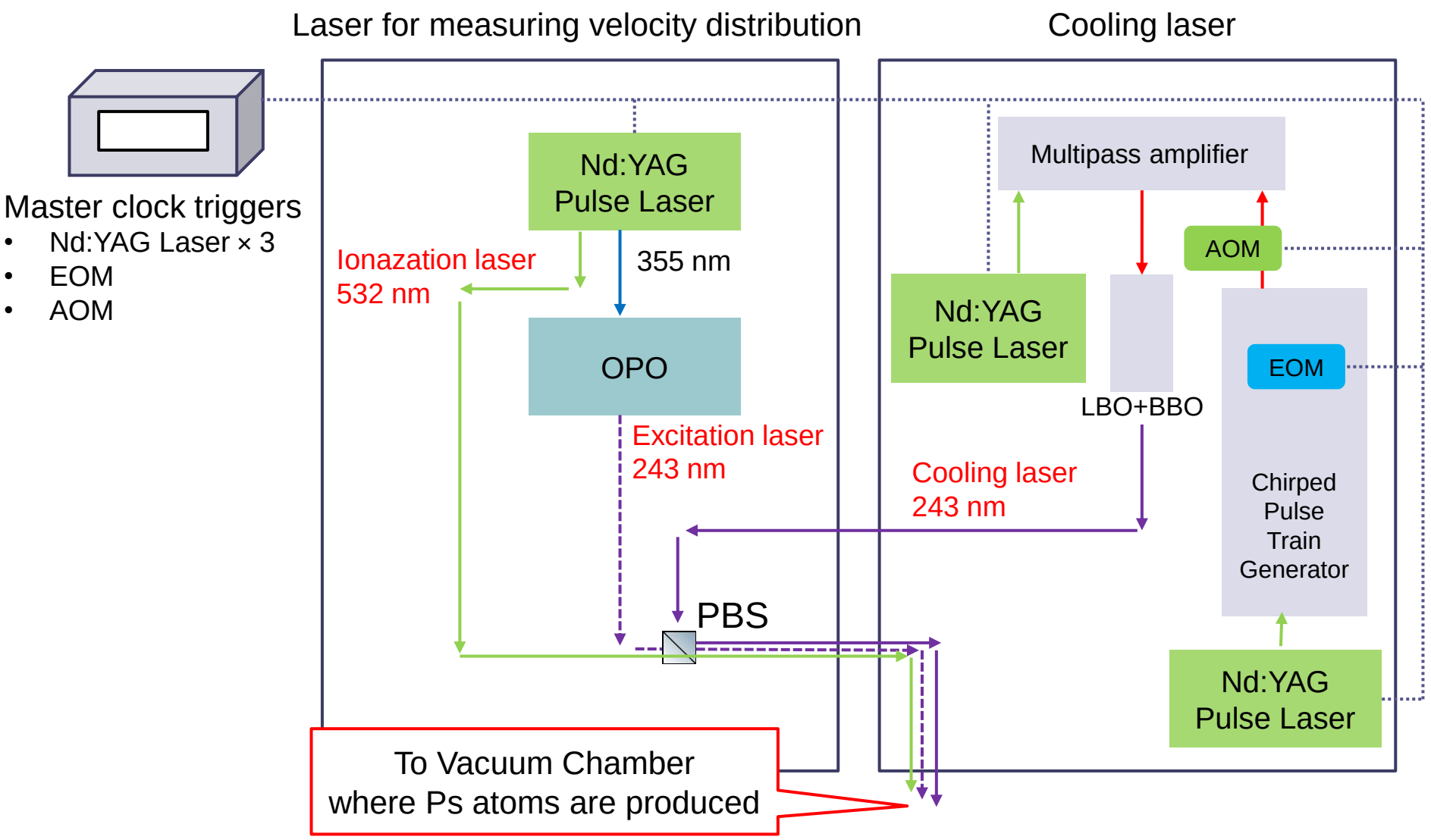


High Energy Accelerator Research Organization (KEK)





Laser system for prototypical laser cooling



Summary

- Ps-BEC is the best candidate for the first antimatter BEC
- Laser cooling of Ps using the 1S-2P transition is a promising method for rapid cooling of Ps well below 100 K

  Requirements for laser cooling of Ps

  1. A broadband spectrum and a frequency chirp to overcome the large Doppler broadening
  2. A long pulse duration comparable to the lifetime of Ps

Result

- We developed the unique laser for cooling Ps

  1. A train of short pulses inside the 300-ns-long contour (approximately 2 times as long as the annihilation lifetime of Ps)
  2. Spectral broadening by EO modulation spanning over 200 GHz in total and two characteristic peaks in the spectrum
  3. A rapid frequency chirp (±42 GHz/μs) in the positive and negative directions

Next steps

- Demonstration of laser cooling of Ps atoms, using the current prototypical laser
- Update the specification of the cooling laser for more efficient cooling of Ps